R-parity violating $U(1)'$-extended MSSM

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Seminar at Johns Hopkins University (Apr. 2, 2008)

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: $U(1)'$ as an alternative to R-parity

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Outline

- Companion symmetry of SUSY
  - Why R-parity?
  - Why $U(1)'$ gauge symmetry?
- R-parity violating SUSY model
  - Proton stability
  - Dark matter issue

Supersymmetry

General SUSY

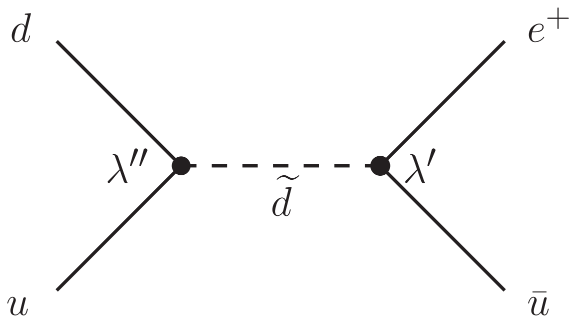
$$\begin{aligned} W &= \mu H_u H_d \\ &+ y_E H_d L E^c + y_D H_d Q D^c + y_U H_u Q U^c \\ &+ \lambda L L E^c + \lambda' L Q D^c + \mu' L H_u + \lambda'' U^c D^c D^c \\ &+ \frac{\eta_1}{M} QQQL + \frac{\eta_2}{M} U^c U^c D^c E^c + \cdots \end{aligned}$$

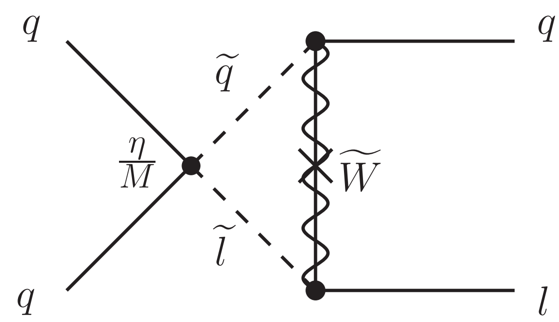
1. μ-problem: $\mu \sim \mathcal{O}$(EW) to avoid fine-tuning in the EWSB.

(Kim, Nilles [1984])

2. lepton number ($\mathcal{L}$) and/or baryon number ($\mathcal{B}$) violating terms at renormalizable and non-renormalizable levels: **one of the most general predictions of SUSY.**

Proton decay





[Dim 4 $\mathcal{L}$ violation $\&$ Dim 4 $\mathcal{B}$ violation]

$\lambda L L E^c + \lambda' L Q D^c$ & $\lambda'' U^c D^c D^c$

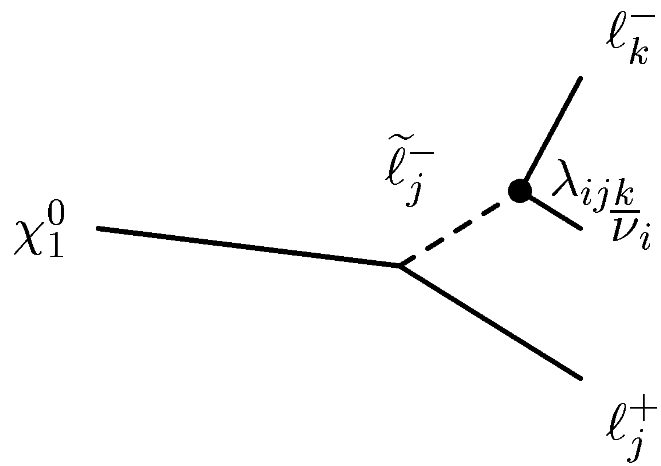
[Dim 5 $\mathcal{B}\&\mathcal{L}$ violation]

$\frac{\eta_1}{M} QQQL + \frac{\eta_2}{M} U^c U^c D^c E^c$

To satisfy $\tau_p \gtrsim 10^{29}$ years,

- Dim 4: $|\lambda_{\rm LV} \cdot \lambda_{\rm BV}| \lesssim 10^{-27}$ (if one is 0, the other can be sizable)
- Dim 5: $|\eta| \lesssim 10^{-7}$ $($for $M = M_{Pl})$

Lightest superparticle (LSP) decay



$$\Gamma = \lambda_{ijk}^2 \frac{\alpha}{128\pi^2} \frac{m_{\chi_1^0}^5}{m_{\widetilde{f}}^4}$$ (for $\chi_1^0 \sim$ photino)

To be a viable dark matter, $\tau_{LSP} \gtrsim 14 \times 10^9$ years (Universe age).

$$|\lambda|, |\lambda'|, |\lambda''| \lesssim 10^{-20}$$

SUSY needs a companion mechanism or symmetry.

Supersymmetry + R-parity

R-parity (or matter parity)

R-parity is defined on component fields, and matter parity is defined on superfields. They are equivalent.

$$
\begin{aligned}
R-\text{parity} \quad &: \quad P_R = (-1)^{3(\mathcal{B}-\mathcal{L})+2s} \\
\text{Matter parity} \quad &: \quad P_M = (-1)^{3(\mathcal{B}-\mathcal{L})}
\end{aligned}
$$

	Q	U^c	D^c	L	E^c	H_u	H_d
Matter parity	1	1	1	1	1	0	0

- LSP is absolutely stable (dark matter candidate).

SUSY with R-parity

$$
\begin{aligned}
W_{R_p} &= \mu H_u H_d \\
&+ y_E H_d L E^c + y_D H_d Q D^c + y_U H_u Q U^c \\
&+ \cdots \\
&+ \frac{\eta_1}{M} QQQL + \frac{\eta_2}{M} U^c U^c D^c E^c + \cdots
\end{aligned}
$$

1. μ-problem: Not addressed.

2. over-constraining of the R-parity: All renormalizable $\mathcal{L}$ violating and $\mathcal{B}$ violating terms (unnecessarily) are forbidden.

3. under-constraining of the R-parity: Dimension 5 $\mathcal{L}\&\mathcal{B}$ violating terms still mediate too fast proton decay.

$\longrightarrow$ Look for an additional or alternative explanation (symmetry).

Supersymmetry + R-parity + $U(1)'$ gauge symmetry

TeV scale $U(1)'$ gauge symmetry

Natural scale of $U(1)'$ in SUSY models is TeV (linked to soft term scales).

$\longrightarrow$ provides a natural solution to the μ-problem.

($z[F]$: $U(1)'$ charge of F)

Two conditions to "**solve the μ-problem**".

- $\mu H_u H_d$: forbidden $\qquad z[H_u] + z[H_d] \neq 0$
- $h S H_u H_d$: allowed $\qquad z[S] + z[H_u] + z[H_d] = 0$

S is a Higgs singlet that breaks the $U(1)'$ spontaneously.

$$\mu_{\text{eff}} = h \langle S \rangle \sim \mathcal{O}(\text{EW}/\text{TeV})$$

SUSY with R-parity and $U(1)'$

$$
\begin{aligned}
W_{R_p+U(1)'} &= hSH_uH_d \\
&+ y_E H_d L E^c + y_D H_d Q D^c + y_U H_u Q U^c \\
&+ \cdots \\
&+ \left(\frac{\eta_1}{M} QQQL + \frac{\eta_2}{M} U^c U^c D^c E^c + \cdots \right)
\end{aligned}
$$

1. μ-problem: Resolved by replacing μ with μ_{eff}.
2. over-constraining of the R-parity: It forbids all renormalizable terms.
3. non-renormalizable terms: Maybe forbidden depending on charges.

$\longrightarrow$ Usual set up of the $U(1)'$-extended MSSM (UMSSM).

In principle, the $U(1)'$ can embed the R-parity (matter parity), which is more economic than having 2 companion symmetries.

LSP dark matter candidates in the UMSSM (brief review)

A viable dark matter candidate should

1. be neutral, stable, cold
2. give right relic density
   ($\Omega_{\rm DM} h^2 = 0.111^{+0.011}_{-0.015}$ from 2σ WMAP+SDSS)
3. avoid direct detection constraint
   ($\sigma_n^{\rm SI} \lesssim 10^{-7}{\rm pb}$ from CDMS/XENON)

Cold dark matter candidates stable under R-parity:

- neutralino (χ^0) LSP
- sneutrino ($\widetilde{\nu}$) LSP

Neutralino LSP dark matter candidate

- UMSSM : 6×6 matrix, in the basis of $\{\widetilde{B}, \widetilde{W}_3, \widetilde{H}_d^0, \widetilde{H}_u^0, \widetilde{S}, \widetilde{Z}'\}$

$$\begin{pmatrix} M_1 & 0 & -g_1 v_d/2 & g_1 v_u/2 & 0 & 0 \\ 0 & M_2 & g_2 v_d/2 & -g_2 v_u/2 & 0 & 0 \\ -g_1 v_d/2 & g_2 v_d/2 & 0 & -\mu_{\rm eff} & -\mu_{\rm eff} v_u/s & g_{Z'} z[H_d] v_d \\ g_1 v_u/2 & -g_2 v_u/2 & -\mu_{\rm eff} & 0 & -\mu_{\rm eff} v_d/s & g_{Z'} z[H_u] v_u \\ 0 & 0 & -\mu_{\rm eff} v_u/s & -\mu_{\rm eff} v_d/s & 0 & g_{Z'} z[S] s \\ 0 & 0 & g_{Z'} z[H_d] v_d & g_{Z'} z[H_u] n_u & g_{Z'} z[S] s & M_{1'} \end{pmatrix}$$

- MSSM : First 4×4 submatrix

$\longrightarrow$ Easy to satisfy the relic density and direct detection constraints, since it has MSSM components which already do.

(Barger, Kao, Langacker, HL [hep-ph/0408120]) (Barger et al. [2007])

Sneutrino LSP dark matter candidate

- Pure left-handed sneutrino ($\widetilde{\nu}_L$):

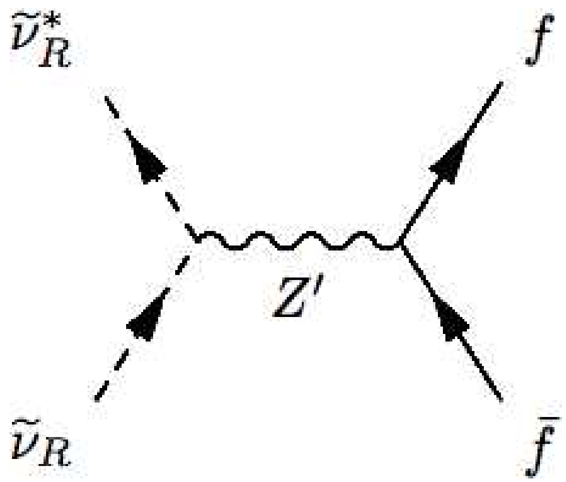
Z mediated channels for sneutrino LSP has too large direct detection cross-section when it makes the right relic density.

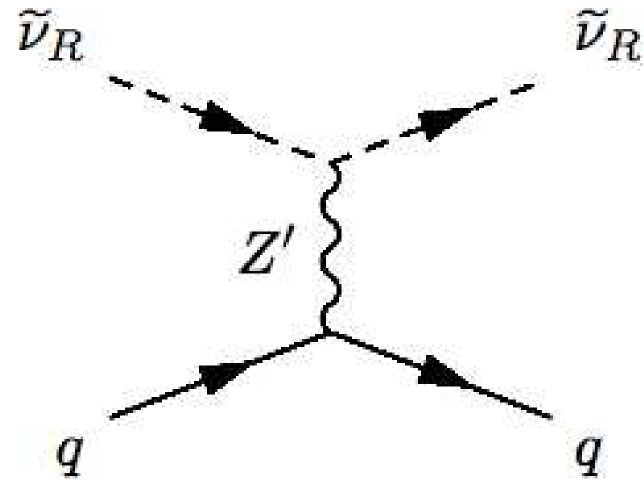
(Falk, Olive, Srednicki [1994])

$$\sigma_n^{\rm SI} \sim G_F^2 \mu_{n-{\rm DM}}^2 \sim 0.1{\rm pb} \gg 10^{-7}{\rm pb} \;\; ({\rm CDMS/XENON})$$

- Predominantly right-handed sneutrino ($\widetilde{\nu}_R$):

  N^c: necessary for the neutrino mass (LH_uN^c).

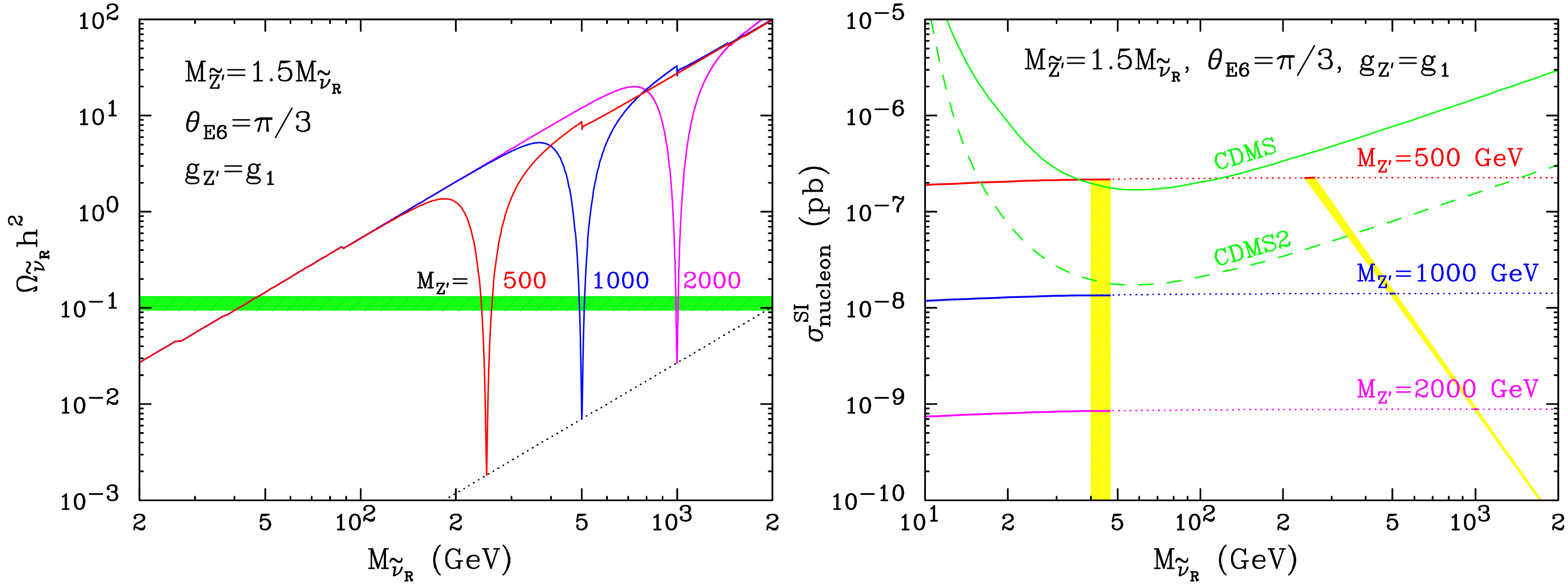




Z' mediated interaction can be suppressed by its mass and coupling.

(HL, Matchev, Nasri [hep-ph/0702223])

Predictions of relic density and direct detection cross-section



Yellow bands: right relic density ($\Omega_{\tilde{\nu}_R}h^2 \sim 0.1$) in the $\widetilde{Z}'$ mediation region ($M_{\tilde{\nu}_R} \sim 45$ GeV) and Z' mediation region ($M_{\tilde{\nu}_R} \sim M_{Z'}/2$).

$\longrightarrow$ **Sneutrino LSP is a viable thermal dark matter candidate in the $U(1)'$-extended MSSM.**

Supersymmetry + $U(1)'$ gauge symmetry
without R-parity

Now, we consider the R-parity violating scenario.

Goal

Construct a stand-alone TeV scale SUSY model without

- over-constraining $\mathcal{L}$, $\mathcal{B}$ violating terms
- μ-problem
- **proton decay problem (including dim 5 operator issue)**
- **dark matter problem (non-LSP dark matter)**

In other words, we will try to construct a R-parity violating $U(1)'$-extended MSSM as an alternative to the usual R-parity conserving MSSM.

Proton stability among the MSSM fields

HL, Matchev, Wang [arXiv:0709.0763]

Free parameters of the MSSM fields charges

Consider the MSSM Yukawa, effective μ-term, $[SU(2)_L]^2 - U(1)'$ anomaly condition.

$$\begin{aligned}
H_u Q U^c &: \quad z[H_u] + z[Q] + z[U^c] = 0 \\
H_d Q D^c &: \quad z[H_d] + z[Q] + z[D^c] = 0 \\
H_d L E^c &: \quad z[H_d] + z[L] + z[E^c] = 0 \\
S H_u H_d &: \quad z[S] + z[H_u] + z[H_d] = 0 \\
A_{221'} &: \quad 3(3z[Q] + z[L]) + (z[H_d] + z[H_u]) + \delta = 0
\end{aligned}$$

with $\delta \equiv A_{221'}[SU(2)_L \text{ exotics}] = 0$ (assume no $SU(2)_L$ exotics).

8 unknown $U(1)'$ charges ($Q, U^c, D^c, L, E^c, H_u, H_d, S$) - 5 conditions = 3 free parameters.

General solution for MSSM fields

$$\begin{pmatrix} z[Q] \\ z[U^c] \\ z[D^c] \\ z[L] \\ z[E^c] \\ z[H_d] \\ z[H_u] \\ z[S] \end{pmatrix} = \alpha \begin{pmatrix} 1 \\ -4 \\ 2 \\ -3 \\ 6 \\ -3 \\ 3 \\ 0 \end{pmatrix} + \beta \begin{pmatrix} 1 \\ -1 \\ -1 \\ -3 \\ 3 \\ 0 \\ 0 \\ 0 \end{pmatrix} + \gamma \begin{pmatrix} 1 \\ 8 \\ -1 \\ 0 \\ 0 \\ 0 \\ -9 \\ 9 \end{pmatrix}$$

1st vector $\propto$ hypercharge (y), 2nd vector $\propto \mathcal{B} - \mathcal{L}$.

$$\alpha = -\frac{z[H_d]}{3} \quad \beta = \frac{z[H_d] - z[L]}{3} \quad \gamma = \frac{z[S]}{9}$$

Lepton number violating terms

Since we already have

$$y_E H_d L E^c,\ y_D H_d Q D^c,\ h S H_u H_d$$

allowing the $\mathcal{L}$ violating terms means

$$\lambda L L E^c,\ \lambda' L Q D^c,\ h' S H_u L \quad \longleftrightarrow \quad z[H_d] = z[L].$$

Renormalizable $\mathcal{L}$ violating couplings (λ, λ', μ') are either all allowed or all forbidden by the $U(1)'$.

LV-BV separation

From MSSM Yukawa and $[SU(2)_L]^2 - U(1)'$ anomaly,

$$z[U^c D^c D^c] - z[LLE^c] + \frac{2}{3}(z[H_u H_d]) = 0$$

BV term LV term original μ-term

- $z[H_u H_d] \neq 0$ (μ-problem solution).
- Either $z[U^c D^c D^c]$ or $z[LLE^c]$ should be non-zero (forbidden).

LV-BV separation: **The LV terms (λLLE^c, $\lambda' LQD^c$) and the BV term ($\lambda'' U^c D^c D^c$) cannot coexist.**

$$\lambda_{LV} \cdot \lambda_{BV} = 0$$

$\longrightarrow$ Proton does not decay through the MSSM dimension 4 operators in the UMSSM.

Also the dimension 5 LV and BV operators ($QQQL$, $U^cU^cD^cE^c$) are automatically forbidden.

$$z[QQQL] = -\frac{1}{3} z[H_u H_d] \neq 0$$
$$z[U^cU^cD^cE^c] = -\frac{5}{3} z[H_u H_d] \neq 0$$

Proton is sufficiently (up to dimension 5 level) stable among the MSSM fields in the R-parity violating $U(1)'$-extended MSSM.

Exotic colors

$[SU(3)_C]^2 - U(1)'$ anomaly free condition:

$$\underbrace{3(2z[Q] + z[U^c] + z[D^c])} + A_{331'}[\text{exotic colors}] = 0$$

$$= -3(z[H_u] + z[H_d]) \neq 0 \;\; (\mu\text{-problem solution})$$

due to the MSSM Yukawas.

$$\rightarrow A_{331'}[\text{exotic colors}] \neq 0$$

Solving the μ-problem requires colored exotics. (Well-known)

For definiteness, we assume three $SU(3)_C$ triplet (K_i) and antitriplet (K_i^c), which are $SU(2)_L$ singlets.

$$W_{\text{exotic colors}} = \eta_{ij} S K_i K_j^c$$

Right-handed neutrinos (N^c)

Observed neutrino mass ($m_\nu \lesssim 0.1$ eV) needs an explanation.

1. Majorana neutrino: with see-saw mechanism

   (Minkowski [1977]) (Yanagida [1979]) (Mohapatra, Senjanovic [1980]) (Gell-Mann, Ramond, Slansky [1980])

$$W = y_N H_u L N^c + m N^c N^c$$

2. Dirac neutrino: natural suppression possible in $U(1)'$ model

   (Langacker [1998])

$$W = y_N \left(\frac{S}{M}\right)^a H_u L N^c$$

3. Lepton number violation: in the LV case

   (Hall, Suzuki [1984]) (Grossman, Haber [1998])

$$W = \mu' H_u L + \lambda L L E^c + \lambda' L Q D^c$$

The BV case ($\lambda'' U^c D^c D^c$) case can provide neutrino mass only through Dirac neutrino. (It does not allow $N^c N^c$, LLE^c, LQD^c, $H_u L$.)

General solution of the MSSM fields including N^c

We allow the (possibly high-dimensional) Dirac neutrino mass term in both LV and BV cases.

$$W = y_N \left(\frac{S}{M}\right)^a H_u L N^c$$

It gives $z[H_u] + z[L] + z[N^c] + az[S] = 0$ and

$$\begin{pmatrix} z[Q] \\ z[U^c] \\ z[D^c] \\ z[L] \\ z[N^c] \\ z[E^c] \\ z[H_d] \\ z[H_u] \\ z[S] \end{pmatrix} = \alpha \begin{pmatrix} 1 \\ -4 \\ 2 \\ -3 \\ 0 \\ 6 \\ -3 \\ 3 \\ 0 \end{pmatrix} + \beta \begin{pmatrix} 1 \\ -1 \\ -1 \\ -3 \\ 3 \\ 3 \\ 0 \\ 0 \\ 0 \end{pmatrix} + \gamma \begin{pmatrix} 1 \\ 8 \\ -1 \\ 0 \\ 9(1-a) \\ 0 \\ 0 \\ -9 \\ 9 \end{pmatrix}.$$

For the LV case, we have another condition

$$LLE^c : 2z[L] + z[E^c] = 0$$

which reduces one free parameter.

$$\begin{pmatrix} z[Q] \\ z[U^c] \\ z[D^c] \\ z[L] \\ z[N^c] \\ z[E^c] \\ z[H_d] \\ z[H_u] \\ z[S] \end{pmatrix} = \alpha' \begin{pmatrix} 1 \\ -4 \\ 2 \\ -3 \\ 0 \\ 6 \\ -3 \\ 3 \\ 0 \end{pmatrix} + \beta' \begin{pmatrix} 0 \\ 4 \\ -1 \\ 1 \\ 3(1-a) \\ -2 \\ 1 \\ -4 \\ 3 \end{pmatrix}$$

$$z[H_d] = z[L]$$

In the BV case, we have another condition

$$U^c D^c D^c : z[U^c] + 2z[D^c] = 0$$

which reduces one free parameter.

$$\begin{pmatrix} z[Q] \\ z[U^c] \\ z[D^c] \\ z[L] \\ z[N^c] \\ z[E^c] \\ z[H_d] \\ z[H_u] \\ z[S] \end{pmatrix} = \alpha' \begin{pmatrix} 1 \\ -4 \\ 2 \\ -3 \\ 0 \\ 6 \\ -3 \\ 3 \\ 0 \end{pmatrix} + \beta' \begin{pmatrix} 0 \\ 6 \\ -3 \\ 1 \\ 3(2-a)-1 \\ -4 \\ 3 \\ -6 \\ 3 \end{pmatrix}$$

$$z[H_d] = z[L] + \frac{2}{3} z[S].$$

Protecting proton from exotic particles

Proton is stable when MSSM fields are considered.

Is it still stable with exotic particles?

We will address this with the remnant discrete symmetry of the $U(1)'$.

Brief review of residual discrete symmetry of $U(1)'$

Conditions to have $U(1)' \longrightarrow Z_N$

A Z_N emerges from $U(1)'$ if their charges satisfy (after normalization to integers):

- $z[F_i] = q[F_i] + n_i N$
- $z[S] = N$

($z[F_i]$: $U(1)'$ charge, $q[F_i]$: Z_N charge) for each field F_i.

$q[S] = 0$: to keep the discrete symmetry unbroken after the $U(1)'$ symmetry is spontaneously broken by a Higgs singlet S.

(ex) In terms of discrete symmetry, $H_u H_d$ and $S H_u H_d$ are not distinguishable (their total discrete charge is same) by the Z_N.

Discrete symmetry compatible with MSSM sector

Most general Z_N of the MSSM sector (Ibanez, Ross [1992]) is

$$Z_N: \quad g_N = B_N^b L_N^\ell$$

with family-universal cyclic symmetries ($\Phi_i \longrightarrow e^{2\pi i \frac{q_i}{N}} \Phi_i$)

$$B_N = e^{2\pi i \frac{q_B}{N}}, \quad L_N = e^{2\pi i \frac{q_L}{N}}$$

and total discrete charge of Z_N is $q = bq_B + \ell q_L \mod N$.

	Q	U^c	D^c	L	E^c	N^c	H_u	H_d	meaning of q
B_N	0	-1	1	-1	2	0	1	-1	$-\mathcal{B} + y/3$
L_N	0	0	0	-1	1	1	0	0	$-\mathcal{L}$

A discrete charge can be rewritten in terms of $\mathcal{B}$ and $\mathcal{L}$.

$$q = -(b\mathcal{B} + \ell\mathcal{L}) + b(y/3) \mod N$$

with a conserved quantity of $-(b\mathcal{B} + \ell\mathcal{L}) \mod N$.

(ex) Matter parity ($R_2 = B_2 L_2^{-1}$) has

$$q = -(\mathcal{B} - \mathcal{L}) + (y/3) \mod 2.$$

Why 2 free parameters?

8 unknown discrete charges (Q, U^c, D^c, L, E^c, N^c, H_u, H_d)

- 5 superpotential terms ($H_u Q U^c$, $H_d Q D^c$, $H_d L E^c$, $H_u L N^c$, $H_u H_d$)

- 1 hypercharge shift invariance ($q[F_i] \longrightarrow q[F_i] + \alpha y[F_i] \mod N$)

= 2 free parameters

Family non-universal charges?

- Family non-universal discrete charges ($q[F_i]$) ?

  : No, at least in quark sector.

  Mixing of quarks not allowed in contradiction to the CKM matrix.

- Family non-universal $U(1)'$ charges ($z[F_i]$) ?

  : Possible.

  It can still have family universal Z_N, if the condition $z[F_i] = q[F_i] + n_i N$ is kept ($z[F_i]$ is family-dependent if n_i is).

FCNC from family non-universal $U(1)'$ charges

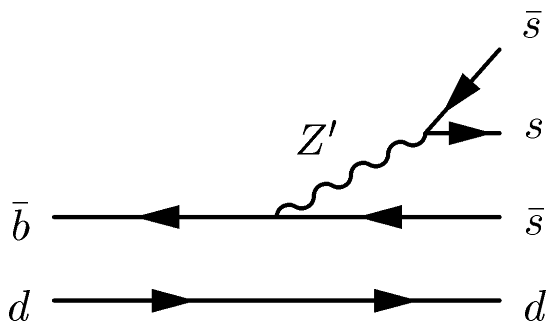
Family non-universal charges may cause FCNC by Z' at tree level. $U(1)'$ coupling matrix in mass eigenstate $(d_L = V_{d_L} d_L^{\rm int})$:

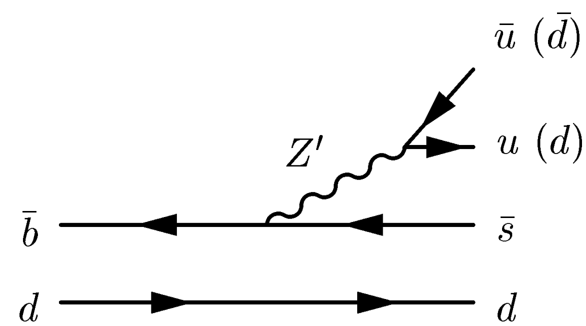
$$B^L \equiv V_{d_L} \epsilon_{d_L} V_{d_L}^\dagger = Q_{d_L} V_{d_L} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1+\delta \end{pmatrix} V_{d_L}^\dagger$$

B^L has off-diagonal terms with phases originated from V_{d_L}. (And similarly for u-type quark and/or Right-handed coupling.) The usual CKM matrix is given by $V_{CKM} = V_{u_L} V_{d_L}^\dagger$.

Flavor changing Z' solution to B anomalies

(Barger, Chiang, Langacker, HL [hep-ph/0310073], [hep-ph/0406126])





$B \to \phi K_S$ $\qquad\qquad$ $B \to \pi K$

FCNC Z' can explain the anomalies in both $B \to \phi K_S$ and $B \to \pi K$.

($B \to \phi K_S$ discrepancy disappeared by now, but the $B \to \pi K$ anomaly still remains a puzzle.)

Remnant discrete symmetry of the RPV-UMSSM

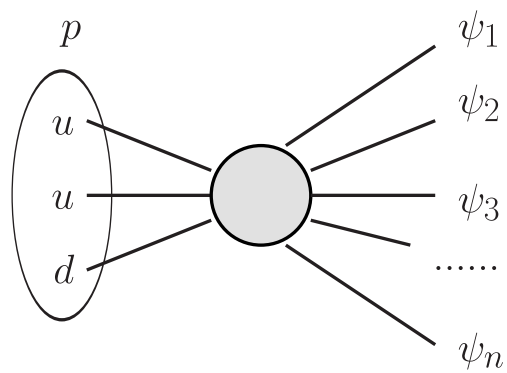
: Proton stability including TeV scale exotics

HL, Luhn, Matchev [arXiv:0712.3505]

Discrete symmetries in presence of exotics

- The discrete symmetries may be changed with additional particles.
- The MSSM discrete symmetries still hold among the MSSM fields.

For a physics process which has only MSSM fields in its effective operators (such as proton decay), we can still discuss with Z_N^{MSSM}.



$$\text{operator[p-decay]} \quad = \quad \left(\frac{1}{M}\right)^m [\underbrace{F_1 F_2 F_3 F_4 F_5 \cdots}_{\text{MSSM fields only}}]$$

Naturally suppressed LV and BV terms

Experimental upper bounds:

$$\begin{aligned} \lambda, \lambda' &\lesssim 10^{-5} \\ \lambda'' &\lesssim 10^{-7} \end{aligned}$$

In the $U(1)'$ model, you can have the naturally suppressed $\mathcal{L}$ and $\mathcal{B}$ violating couplings from high-dimensional operators.

$$\lambda = \widehat{\lambda} \left(\frac{\langle S \rangle}{M} \right)^A$$

It does not affect discrete symmetry argument since $q[S] = 0$.

$$W_{\rm LV} = \widehat{\lambda}\left(\frac{S}{M}\right)^n LLE^c + \widehat{\lambda}'\left(\frac{S}{M}\right)^n LQD^c + \widehat{h}'\left(\frac{S}{M}\right)^n SLH_u$$

$$W_{\rm BV} = \widehat{\lambda}''\left(\frac{S}{M}\right)^m U^cD^cD^c$$

with $\lambda_{\rm eff} = \widehat{\lambda}\left(\frac{\langle S\rangle}{M}\right)^n$, etc.

Generalized LV-BV separation:

$$z[S^mU^cD^cD^c] - z[S^nLLE^c] - \left(\frac{2}{3} + (m-n)\right) z[S] = 0$$

(The LV-BV separation still holds independent of n and m.)

General $U(1)'$ charges in the LV case

Use another condition

$$S^n L L E^c : n z[S] + 2z[L] + z[E^c] = 0$$

to reduce a parameter in the general $U(1)'$ charges.

$$\begin{pmatrix} z[Q] \\ z[U^c] \\ z[D^c] \\ z[L] \\ z[N^c] \\ z[E^c] \\ z[H_d] \\ z[H_u] \\ z[S] \end{pmatrix} = \alpha' \begin{pmatrix} 1 \\ -4 \\ 2 \\ -3 \\ 0 \\ 6 \\ -3 \\ 3 \\ 0 \end{pmatrix} + \beta' \begin{pmatrix} 0 \\ 3(1+n)+1 \\ -3n-1 \\ 1 \\ 3(1-a+n) \\ -3n-2 \\ 3n+1 \\ -3(1+n)-1 \\ 3 \end{pmatrix}$$

$\longrightarrow$ **It is a Z_3 symmetry.** ($N = z[S]$ after normalization to integers)

Discrete symmetry of the LV case

- First column ($\propto y$) is irrelevant $\longrightarrow$ Take $\alpha' = 0$ and $\beta' = 1$.
- $q[F_i] = z[F_i] - n_i N \longrightarrow q[F_i] = z[F_i] \bmod 3$.

$$\begin{pmatrix} q[Q] \\ q[U^c] \\ q[D^c] \\ q[L] \\ q[N^c] \\ q[E^c] \\ q[H_d] \\ q[H_u] \\ q[S] \end{pmatrix} = \begin{pmatrix} 0 \\ 3(1+n)+1 \\ -3n-1 \\ 1 \\ 3(1-a+n) \\ -3n-2 \\ 3n+1 \\ -3(1+n)-1 \\ 3 \end{pmatrix} \bmod 3 = - \begin{pmatrix} 0 \\ -1 \\ 1 \\ -1 \\ 0 \\ -1 \\ -1 \\ 1 \\ 0 \end{pmatrix} \bmod 3$$

Compare with charge table. $\longrightarrow$ **LV model has B_3 (baryon triality).**

	Q	U^c	D^c	L	E^c	N^c	H_u	H_d	meaning of q
B_3	0	-1	1	-1	-1	0	1	-1	$-\mathcal{B} + y/3$

Selection rule of B_3

The discrete charge of B_3 for arbitrary operator is $(-\mathcal{B} + y/3) \bmod 3$.

$$\Delta\mathcal{B} = 3 \times \text{integer}$$

for any process. (Castano, Martin [1994])

It dictates that baryon number can be violated by only $3 \times \text{integer}$ under the B_3.

- Proton decay ($\Delta\mathcal{B} = 1$): Forbidden
- Neutron-antineutron oscillation ($\Delta\mathcal{B} = 2$): Forbidden

Ensuring proton stability in the LV model (B_3)

1. Solve the μ-problem with $U(1)'$ gauge symmetry.

2. Require $\mathcal{L}$ violating terms such as $\lambda' LQD^c$. [B_3 is invoked]

3. **Then proton is absolutely stable!**

General $U(1)'$ charges for the BV case

Use another condition

$$S^m U^c D^c D^c : mz[S] + z[U^c] + 2z[D^c] = 0$$

to reduce a parameter in the general $U(1)'$ charges.

$$\begin{pmatrix} z[Q] \\ z[U^c] \\ z[D^c] \\ z[L] \\ z[N^c] \\ z[E^c] \\ z[H_d] \\ z[H_u] \\ z[S] \end{pmatrix} = \alpha' \begin{pmatrix} 1 \\ -4 \\ 2 \\ -3 \\ 0 \\ 6 \\ -3 \\ 3 \\ 0 \end{pmatrix} + \beta' \begin{pmatrix} 0 \\ 3(2+m) \\ -3(1+m) \\ 1 \\ 3(2-a+m)-1 \\ -3(1+m)-1 \\ 3(1+m) \\ -3(2+m) \\ 3 \end{pmatrix}$$

$\longrightarrow$ **It is a Z_3 symmetry.** ($N = z[S]$ after normalization to integers)

Discrete symmetry of the BV case

- First column ($\propto y$) is irrelevant $\longrightarrow$ Take $\alpha' = 0$ and $\beta' = 1$.
- $q[F_i] = z[F_i] - n_i N \longrightarrow q[F_i] = z[F_i] \bmod 3$.

$$\begin{pmatrix} q[Q] \\ q[U^c] \\ q[D^c] \\ q[L] \\ q[N^c] \\ q[E^c] \\ q[H_d] \\ q[H_u] \\ q[S] \end{pmatrix} = \begin{pmatrix} 0 \\ 3(2+m) \\ -3(1+m) \\ 1 \\ 3(2-a+m)-1 \\ -3(1+m)-1 \\ 3(1+m) \\ -3(2+m) \\ 3 \end{pmatrix} \bmod 3 \;=\; - \begin{pmatrix} 0 \\ 0 \\ 0 \\ -1 \\ 1 \\ 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \bmod 3$$

Compare with charge table. $\longrightarrow$ **BV model has L_3 (lepton triality).**

	Q	U^c	D^c	L	E^c	N^c	H_u	H_d	meaning of q
L_3	0	0	0	-1	1	1	0	0	$-\mathcal{L}$

Selection rule of L_3

The discrete charge of L_3 for arbitrary operator is $-\mathcal{L} \bmod 3$.

$$\Delta\mathcal{L} = 3 \times \text{integer}$$

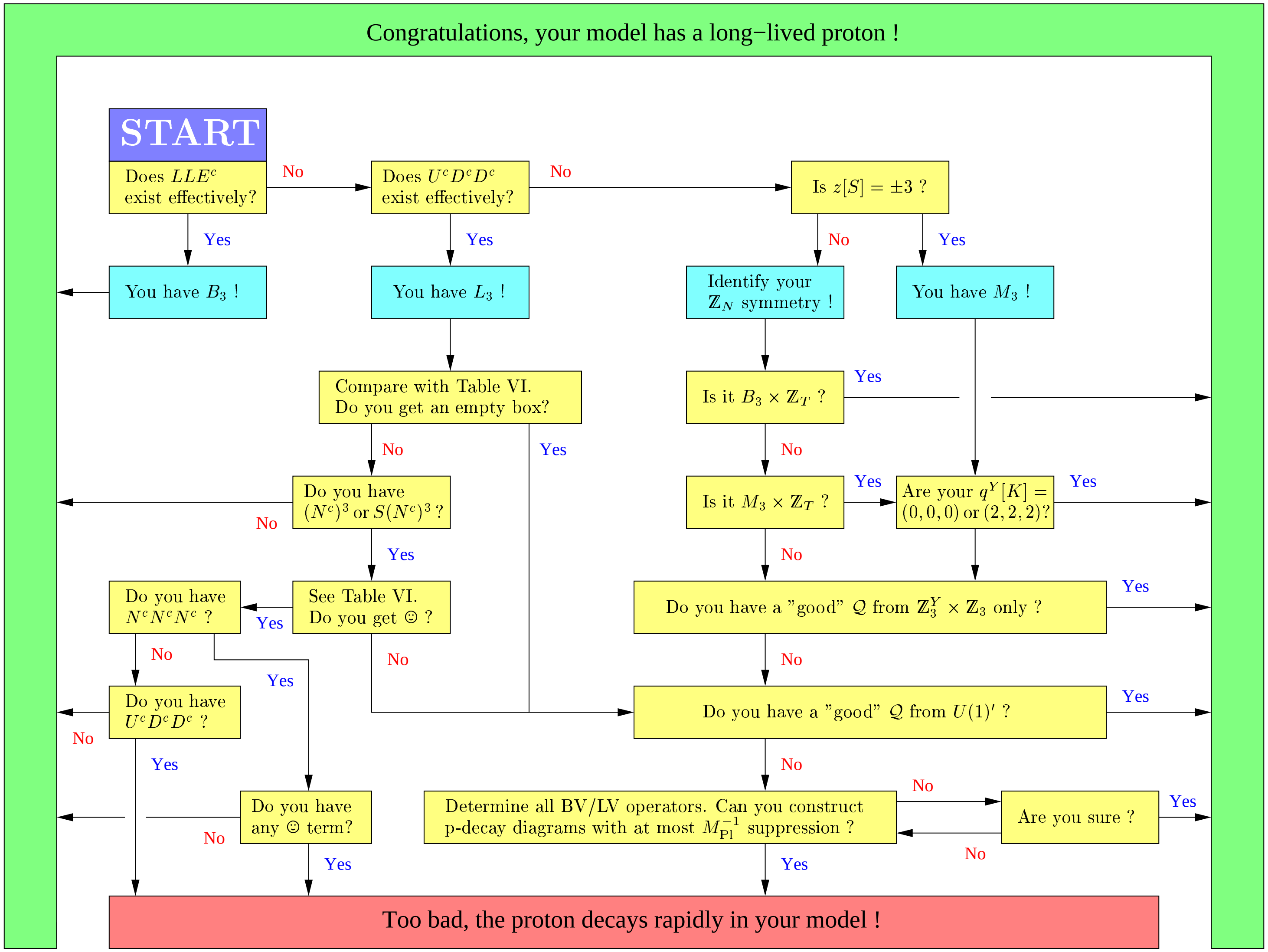
for any process.

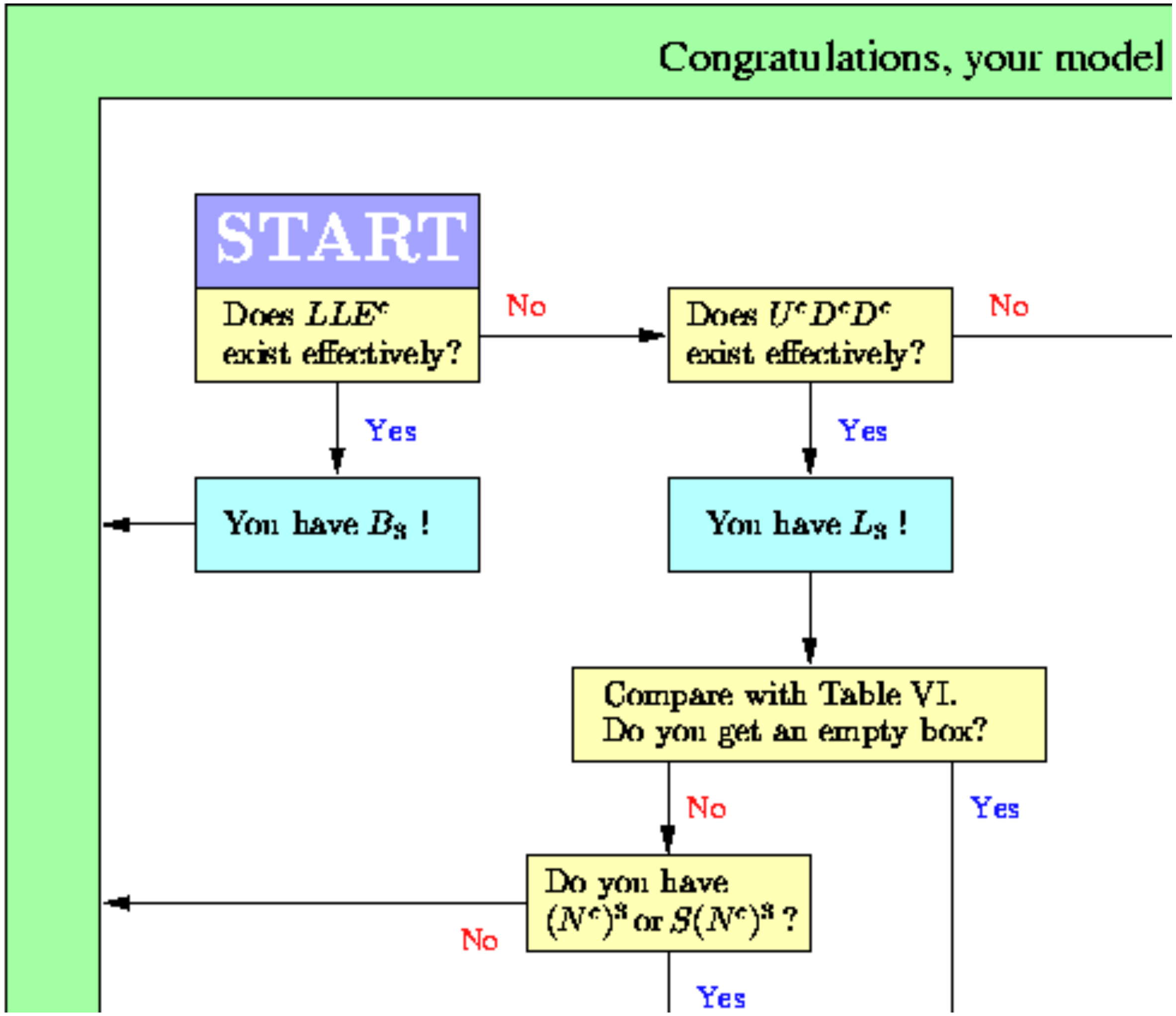
It dictates that $\mathcal{L}$ can be violated by only $3 \times \text{integer}$ under the L_3.

- $0\nu\beta\beta$ decay ($\Delta\mathcal{L} = 2$): Forbidden

Proton still may decay if the decay products has 3, 6, $\cdots$ leptons. (Discrete symmetry argument is not enough. $\longrightarrow$ Need to consider the $U(1)'$ symmetry and exotic fields (model-dependent) to ensure proton stability.)

Flowchart to check proton stability




Congratulations, your model
START
Does LLE^c exist effectively?
No
Does $U^cD^cD^c$ exist effectively?
No
Yes
Yes
You have B_3 !
You have L_3 !
Compare with Table VI.
Do you get an empty box?
No
Yes
Do you have $(N^c)^3$ or $S(N^c)^3$?
No
Yes

Ensuring proton stability in the BV model (L_3)

1. Solve the μ-problem with $U(1)'$ gauge symmetry.
2. Require $\mathcal{B}$ violating term $\lambda'' U^c D^c D^c$. [L_3 is invoked]
3. Forbid $N^c N^c N^c$ and $S N^c N^c N^c$ by the $U(1)'$ charges[a].
4. **Then proton is sufficiently (up to dimension 5) stable!**

[a]It holds in our choice of colored exotics (K_i, K_i^c) which have integer hypercharges (under normalization of $y[Q] = 1$).

Examples of anomaly-free $U(1)'$ charge assignments with stable proton

Free to be scaled by any normalization and shifted by hypercharge.

	LV (B_3)					BV (L_3)					
	I	II	III	IV	V	I	II	III	IV	V	VI
$z[Q]$	1	3	3	3	4	1	3	15	0	0	0
$z[U^c]$	8	24	24	24	5	2	6	30	3	9	9
$z[D^c]$	-1	-3	-3	-3	-4	-1	-3	-15	0	0	0
$z[L]$	0	0	0	0	-9	-2	-6	-30	1	3	3
$z[E^c]$	0	0	0	0	9	2	6	30	-1	-3	-3
$z[N^c]$	0	0	0	0	9	2	6	30	-1	-3	-3
$z[H_u]$	-9	-27	-27	-27	-9	-3	-9	-45	-3	-9	-9
$z[H_d]$	0	0	0	0	0	0	0	0	0	0	0
$z[S]$	9	27	27	27	9	3	9	45	3	9	9
$z[K_1]$	-5	-13	-23	-25	-5	-1	-7	-17	-3	-7	-5
$z[K_2]$	-2	-4	-8	-7	-5	-1	-4	-20	0	-1	1
$z[K_3]$	1	2	1	-1	-5	-1	-4	-11	0	2	1
$z[K_1^c]$	-4	-14	-4	-2	-4	-2	-2	-28	0	-2	-4
$z[K_2^c]$	-7	-23	-19	-20	-4	-2	-5	-25	-3	-8	-10
$z[K_3^c]$	-10	-29	-28	-26	-4	-2	-5	-34	-3	-11	-10

$y[K_i] = \{\frac{1}{3}, -\frac{2}{3}, -\frac{2}{3}\}$

What is left?

Our goal was to construct a stand-alone TeV scale SUSY model without

- μ-problem: Ok
- over-constraining R-parity violating terms: Ok
- **proton decay problem (including dim 5 operator issue): Ok**
- **dark matter problem: ?**

A R-parity violating $U(1)'$-extended MSSM can do first three.

What about the dark matter issue?

A dark matter candidate without introducing an independent symmetry?

LUP dark matter
(in the R-parity conserving UMSSM)

Hur, HL, Nasri [arXiv:0710.2653]

SM-singlet (hidden sector) neutral and massive particle

In the $U(1)'$ model, **SM-singlet exotics (X)** are often required to cancel some anomaly cancellations.

- $[\text{gravity}]^2 - U(1)'$: $\sum_i z[F_i] = \cdots + z[X] = 0$
- $[U(1)']^3$: $\sum_i z[F_i]^3 = \cdots + z[X]^3 = 0$

They are neutral particles.

$\longrightarrow$ Potentially a new dark matter candidate if they are stable.

We consider SM-singlet exotics X (Majorana fields for simplicity).

$$W_{\text{hidden}} = \frac{\xi_{jk}}{2} S X_j X_k$$
$$\to z[X] = -\frac{1}{2} z[S]$$

How to stabilize hidden sector field?

Invoke a residual discrete symmetry (Z_2) of the $U(1)'$ for the hidden sector.

$$Z_2^{hid}: \quad g_2^{hid} = U_2 \qquad (U\text{-parity})$$

	Q	U^c	D^c	L	E^c	N^c	H_u	H_d	X	meaning of q
U_2	0	0	0	0	0	0	0	0	-1	$-\mathcal{U}$ (X number)

$$U_p[\text{MSSM}] = \text{even}, \quad U_p[X] = \text{odd}$$

(Other exotics: assumed to be heavier than the X.)

- LUP: Lightest X (either fermionic(ψ_X) or scalar(ϕ_X) component)

$\longrightarrow$ **LUP (neutral, massive, and stable) is a dark matter candidate.**

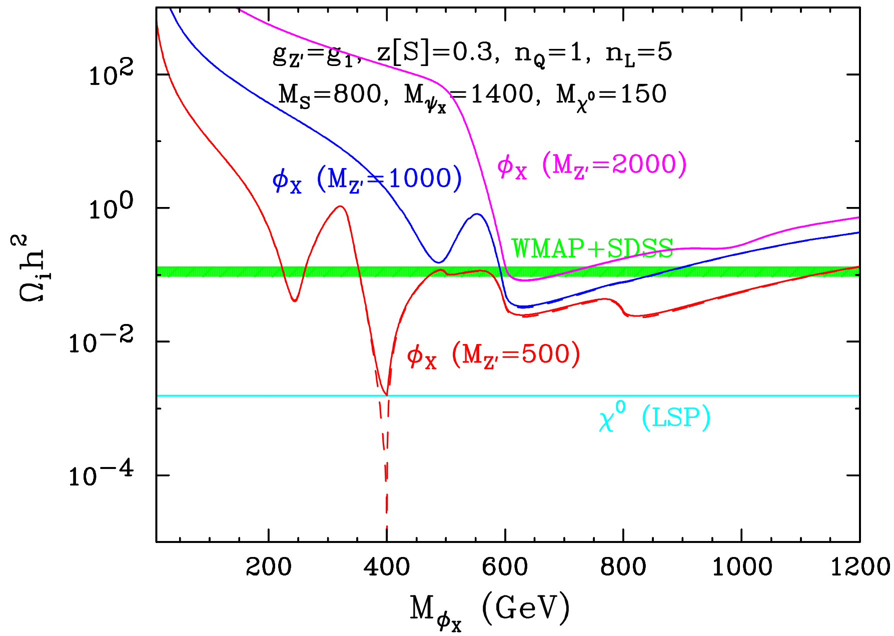
Annihilation channels for the LUP dark matter

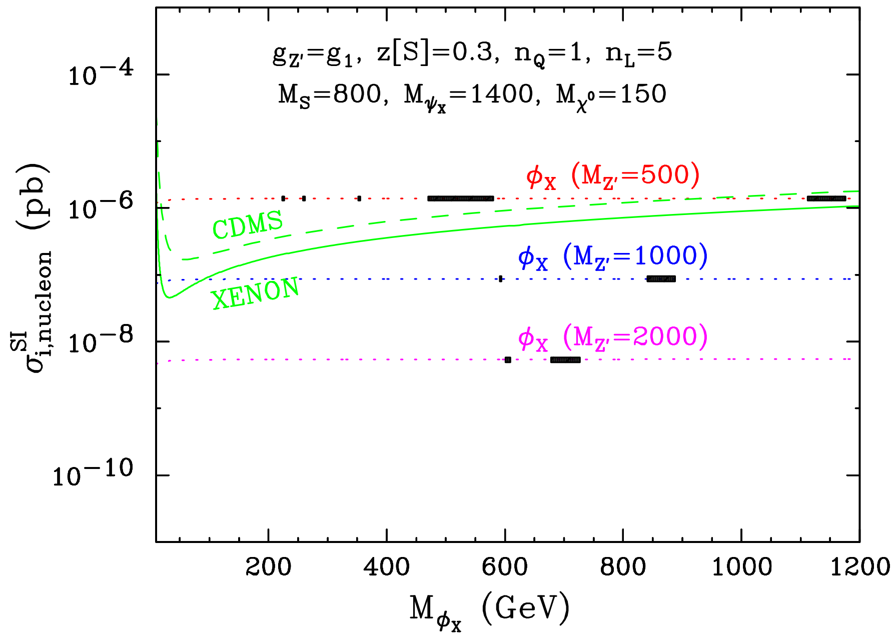
For ψ_X (fermionic) LUP,

1. $\psi_X \psi_X \to f \bar{f}$ (Z' mediated s-channel)
2. $\psi_X \psi_X \to \widetilde{f} \widetilde{f}^*$ (S mediated s-channel, Z' mediated s-channel)
3. $\psi_X \psi_X \to SS$, $Z'Z'$ (S mediated s-channel, ψ_X mediated t-ch)
4. $\psi_X \psi_X \to SZ'$ (Z' mediated s-channel, ψ_X mediated t-channel)
5. $\psi_X \psi_X \to \widetilde{S} \widetilde{S}$ (Z' mediated s-channel, ϕ_X mediated t-channel)
6. $\psi_X \psi_X \to \widetilde{Z}' \widetilde{Z}'$ (ϕ_X mediated t-channel)
7. $\psi_X \psi_X \to \widetilde{S} \widetilde{Z}'$ (S mediated s-channel, ϕ_X mediated t-channel)

and also similarly for ϕ_X (scalar) LUP.

Predictions of relic density and direct detection cross-section





[Simulated by `micrOMEGAs` with a newly constructed UMSSM model file]

LSP + LUP multiple dark matters can satisfy both the relic density and direct detection constraints.

Multiple dark matters scenario with R-parity and U-parity

LUP was first introduced in a R-parity conserving $U(1)'$-extended MSSM.

- R-parity: for proton stability (at renormalizable level)

  $\longrightarrow$ LSP dark matter (SM charged particle: MSSM sector)

- U-parity: as a remnant of $U(1)'$

  $\longrightarrow$ LUP dark matter (SM uncharged particle: hidden sector)

For each sector, discrete symmetries came from different origins.

Residual discrete symmetry extended to hidden sector

: LUP dark matter in the RPV-UMSSM

HL [arXiv:0802.0506]

Two discrete symmetries

Z_N is isomorphic (structure-preserving mapping in both directions) to $Z_{N_1} \times Z_{N_2}$, if N_1 and N_2 are coprime (their GCD = 1) and $N = N_1 N_2$.

$$Z_N = Z_{N_1} \times Z_{N_2}$$

(ex: $Z_6 = Z_2 \times Z_3$).

What does it mean?

- No need of two gauge origins for Z_{N_1}, Z_{N_2} (if N_1, N_2 coprime).

$$U(1)' \rightarrow Z_{N_1}, \quad U(1)'' \rightarrow Z_{N_2}$$

- **Only one $U(1)$ which has Z_N as a residual discrete symmetry.**

$$U(1)' \rightarrow Z_N = Z_{N_1} \times Z_{N_2}$$

Discrete symmetries over the MSSM and the hidden sectors

Consider $Z_N^{tot} = Z_{N_1}^{obs} \times Z_{N_2}^{hid}$ (where N_1 and N_2 are coprime) as the most general remnant residual discrete symmetry from **a common $U(1)'$ gauge symmetry**.

$$
\begin{aligned}
Z_N^{tot} : \; g_N^{tot} &= B_{N_1}^{b} L_{N_1}^{\ell} \times U_{N_2}^{u} \\
&= B_N^{bN_2} L_N^{\ell N_2} U_N^{u N_1}
\end{aligned}
$$

Simplest example: $U(1)' \to Z_6 (= B_3 \times U_2)$

The remnant discrete symmetry of the $U(1)'$ is therefore

$$Z_6^{tot}: \;\; g_6^{tot} = B_6^2 U_6^3$$

and its total discrete charge is given by $q = 2q_B + 3q_U \bmod 6$.

$$\begin{array}{lll} q[Q] = 0 & q[U^c] = -2 & q[D^c] = 2 \\ q[L] = -2 & q[E^c] = -2 & q[N^c] = 0 \\ q[H_u] = 2 & q[H_d] = -2 & q[X] = -3 \end{array}$$

(Other exotic fields: assumed to be heavier than proton and the LUP $\longrightarrow$ not stable due to the discrete symmetry.)

A unified picture of the stabilities in the observable and hidden sectors

$$U(1)' \to Z_{N_1}^{obs} \times Z_{N_2}^{hid}$$

MSSM sector		Hidden sector
$Z_{N_1}^{obs}\ (B_3)$	—	$Z_{N_2}^{hid}\ (U_2)$
: stable proton		: stable dark matter

A single $U(1)'$ gauge symmetry provides absolute stabilities for proton (MSSM sector) and dark matter (hidden sector).

Gravitino problem of the GMSB

In the gauge mediated SUSY breaking (GMSB) scenario, gravitino is the LSP.

$$\left(m_{3/2} \sim \frac{\langle F \rangle}{M_{Pl}} \right) \ll \left(m_{\text{soft}} \sim \frac{\alpha_a}{4\pi} \frac{\langle F \rangle}{M_{\text{mess}}} \right)$$

The gravitino relic density (assuming R-parity) is approximately given by (Pagels, Primack [1982])

$$\Omega_{3/2} h^2 \sim \frac{m_{3/2}}{1\ \text{keV}}.$$

Dark matter relic density constrains $m_{3/2} \sim \mathcal{O}(\text{keV})$

$\longrightarrow$ **warm dark matter**, which cannot explain the matter power spectrum. (Viel et al. [2005])

Cure of gravitino problem with LUP dark matter with R-parity violation

When the LUP is the only (or dominant), there is no conflict with matter power spectrum.

- lighter gravitino LSP ($m_{3/2} \ll 1 \text{ keV}$): maybe still long-lived (small coupling and mass) as a subdominant dark matter
- heavier gravitino LSP ($m_{3/2} \gg 1 \text{ keV}$): decays through the R-parity violating couplings

The next-to-lightest superparticle (NLSP) will decay into the SM particles through the R-parity violating processes before BBN.

$\longrightarrow$ **LUP in RPV model can be an appealing solution to the gravitino problem.** (Need numerical study).

Future studies

1. Extension of the hidden sector fields to the Dirac particles (Z_N^{hid} with $N \geq 2$ is possible), and explicit model buildings including L_3 etc.

2. Collider signals (RPV signals, LUP signals).

3. Indirect detection signals of the LUP dark matter.

4. Quantitative study of the solving the gravitino problem.

Summary

R-parity conserving MSSM vs. R-parity violating UMSSM

	R_p	$U(1)' \longrightarrow B_3 \times U_p$
RPV signals	impossible	**possible**
μ-problem	not addressed	**solvable ($U(1)'$)**
proton	unstable w/ dim 5 op. (R_p)	**stable (B_3)**
dark matter	stable LSP (R_p)	**stable LUP (U_p)**
light $\widetilde{G}$ problem	not addressed	**solvable**

Also, a unified picture of stability issues in both sectors.

$$U(1)' \to Z_{N_1}^{obs} \times Z_{N_2}^{hid}$$

MSSM sector

$Z_{N_1}^{obs}$ (B_3)

: stable proton

Hidden sector

$Z_{N_2}^{hid}$ (U_2)

: stable dark matter

In short, TeV scale $U(1)'$ is an attractive alternative to R-parity.